POSSIBLE EXPERIMENTS ON WAVE FUNCTION LOCALIZATION DUE TO COMPTON SCATTERING

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Abstract

The reduction of a particle's wave function in the process of radiation or light scattering is a longstanding problem. Its solution will give a clue on processes that form, for example, wave functions of electrons constantly emitting synchrotron radiation quanta in storage rings. On a more global scale, it may shed light on wave function collapse due to the process of measurement. In this paper we consider various experimental options using Fermilab electron beams and a possible electron beam from the SNS linac and lasers to detect electron wave function change due to Compton scattering.

INTRODUCTION

The first dedicated experiments to measure the wave function of an electron in accelerator were started in Novosibirsk about two decades ago and described in [1, 2]. The experiments showed that the wave function of an electron in a storage ring is very localized, and its motion is similar to the motion of a classical particle with random kicks without any sign of phase space dilution due to the potential well (RF) nonlinearities.

The experiments were performed in the VEPP-3 storage ring with a single circulating electron [2] and the light from an undulator that was detected by photomultipliers. The standard Brown-Twiss intensity interferometer scheme used a splitter to send the photons to two photomultipliers. The basic idea to measure the longitudinal wave function size was to detect two photons by different photomultipliers during one passage of an electron through the undulator and the rms difference in time, multiplied by velocity of light, was supposed to give the wave function size. Unfortunately, the photomultipliers were slow – their response time (called the dispersion in [2]) was around 160 ps. The signal time difference from two photomultipliers was well within this number, therefore it was concluded that the wave function size is much shorter than the available resolution.

Here we pursue another approach. Using scattered instead of radiated quanta, and knowing the precise energy of electrons and photons, we can measure the resulting energy distribution (and, consequently, the electron wave function) after the scattered photon is measured by a detector and after we employ coincidence scheme, i.e. take only pairs of related electrons and Compton photons with very small angle with the beam velocity vector. This results in a very small transverse recoil and the electrons have mostly longitudinal momentum (or energy) change. This is possible if the resolution of detectors is high and the repetition rate of events is low. If the repetition rate is high, the electron beam energy spread in its left shoulder (see Figure 1) gives the energy spread of scattered electrons even without precise knowledge of the measured gamma quanta if the quanta don't introduce a large angular spread for electrons (we discuss this in the next sections).

An experiment outline is shown schematically in Figure 1. An electron beam with very small energy spread from a linac with energy in the range of hundreds of MeV collides with a laser beam producing rare Compton quanta. The backward scattered quanta are measured in a small scattering angle range (to have precise knowledge of their energy) by an X-ray detector and the electron that scattered the quanta is measured in an energy analyser that separates this electron from the rest of the beam by, e.g., magnetic field.

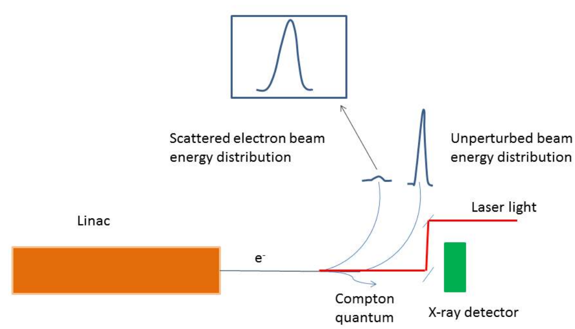

Figure 1: Experiment outline.

If the separation is larger than the width of the electron beam after the magnets, it is possible to measure the width of the energy distribution of the scattered electrons. This distribution, if different from the beam distribution, will give us the wave function width, or its localization, after the process of scattering and measurement of the photon. One has to notice that Figure 1 two-peak discontinuous distribution of electrons can be obtained if we cut out all electron-photon scatterings with large angles of Compton quanta with respect to beam axis pointing toward beam velocity. This procedure will eliminate the scattered-electron angular spread contribution to the left shoulder distribution and as a

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result will give more accurate details on the localization process.

In the next section we present calculations for the process probability and accuracy of the measurement. Last section presents simple estimations for the resulting wave package width – the technique is simple and related to the Heisenberg uncertainty principle.

ESTIMATIONS OF THE MAIN PROCESS PARAMETERS

Here we are interested in estimating for a given Compton quanta flux, the required laser and electron beam parameters, accuracies of the beams alignment, etc.

First of all, the electron beam should be as monochromatic as possible and the Compton quanta energy spread has to be minimal. The energy spread of the scattered electrons includes the energy spread of the incident electron beam and Compton quanta plus energy spread increase due to localization process. The smaller the first contribution is, the larger the accuracy of the energy spread increase measurement will be. In the limit of zero energy spread of the electron beam and Compton quanta energy, the energy spread of the scattered electrons (left screen in Figure 1) is a result of localization process and the Fourier image of the square root of the distribution gives us the localized electron wave function after the Compton quantum measurement (see the discussion of its physics in the last section).

Let's estimate separation of the beams – scattered (left trajectory in Figure 1) and unperturbed (right trajectory in Figure 1). Assuming a head-on collision, for backscattered quanta the energy ε_s is:

$$\varepsilon_s = 4\gamma^2\varepsilon\,, \tag{1}$$

where ε_s is the Compton quanta energy, and γ is the relativistic factor of the electron beam (here and below we assume that we are in Thompson regime, i.e. photon energy in the electron rest frame is much less than the electron rest energy). Assuming the electron energy E=405 MeV for SNS [3] and E=150 MeV for Fermilab IOTA injection line [4] we have roughly 8.8 MeV and 1.2 MeV backscattered quanta for these facilities, respectively, for readily available 355 nm light. More important is the relative energy change that is 2.2 % and 0.67 %, respectively. The typical relative electron beam energy spread is 0.01%. It shows both Fermilab and SNS electron beam energy separation could be made almost two orders of magnitude larger than the spread which gives us opportunity to make clean experiments on wave function localization.

The next step is to calculate the angle for quanta registration to reach the desired accuracy of scattered electron spread and the detection rates. The Compton cross section σ in electron rest frame in the Thompson regime is:

$$d\sigma = \frac{r_e^2}{2}(1+\cos^2\chi)d\Omega\,, \tag{2}$$

where r_e is the classical radius of the electron, and χ is the angle of the scattered photon with respect to the initial angle that is assumed to be exactly (or very close to) 180 degrees with the electron beam direction. We have to register backscattered photons very close to beam axis and, once a photon is registered, detect the scattered electron. In this way we minimize spread of scattered electron energies. If we want it to be small, the angle $\theta=\pi-\chi$ has to be small also. Recalculating the photon energy ε_s from the electron rest frame to laboratory frame yields:

$$\varepsilon_s = 2\gamma^2\varepsilon(1+\beta\cos\theta) \approx 4\gamma^2\varepsilon(1-\frac{\theta^2}{4})\,. \tag{3}$$

The spread of photon energies is about $\varepsilon_s\frac{\theta^2}{4}$, and has to be less than the electron beam energy spread δE which yields:

$$\theta \le 2\sqrt{\frac{\delta E}{E}\frac{E}{\varepsilon_s}}\,. \tag{4}$$

The rough estimate for both facilities (assuming $\frac{\delta E}{E}\approx 10^{-4}$) for 355 nm light is $\theta \le 0.2$ radians. Only photons within this angle have to be collected. We have to recall here that the Compton photon with a large angle gives a transverse kick (around 10^{-3} angle for our maximal angle of 0.2 rad in the beam's rest frame) and this reduces the accuracy of measurement because the electron separation due to dispersion and energy drop of scattered electrons will be smeared by the spread of the horizontal coordinates that appear due to Compton photon transverse momenta. We just have to reduce beta function at interaction region to mitigate this effect. In addition, the dispersion function after the magnets has to be as large as possible and the beta function at the electron position measurement has to be minimized – we leave these details for future work on more detailed design of the beam and laser optics.

At this point we have to estimate the needed electron flux and the detection rates for reasonable lasers. In the laboratory frame this photon angle becomes:

$$\theta_L \approx \frac{\theta}{2\gamma}\,, \tag{5}$$

that is around $0.3\text{x}10^{-3}$ for the Fermilab parameters. It means that the gamma detector, placed 10 meters from the beam, has to have an aperture diameter only 0.6 cm for the Fermilab case. SNS parameters have the similar values. For this small angle the cross section (2) becomes:

$$\sigma = \pi r_e^2\theta^2\,, \tag{6}$$

And the rate f of Compton quanta detection is:

$$f = \sigma f_{ph} N_e / S\,, \tag{7}$$

where f_{ph} is the number of photons per second, N_e is the number of electrons in the interaction volume, and S is the area of beams overlap.

Estimation for the simplest SNS experiment can be done under following assumptions:

1) Electrons come from H^- stripping by a Q-switch laser with duration around 10 ns with repetition rate 30 Hz;
2) Only a small fraction (1%) of ions are stripped to prevent electron beam blow-up due to space charge force, therefore the total number of electrons per one laser shot is N_e=2x10^7;
3) The laser for interaction is also a 30 Hz Q-switch laser with the number of photons = 1.5x10^{18} per pulse assuming 25% efficiency conversion into 355 from 1064 nm light;
4) The area of overlap can be made around 1 mm^2;
5) We assume the electron beam spread can be reduced to 10^{-4} or below – either naturally or using some collimation.

The SNS events rate for 100% efficiency of gamma detector is $f \approx 0.9\,kHz$. This number is too high in order to use coincidence registration for electrons and gamma quanta. Probably, it is not necessary. But we can collimate the beam to reduce the energy spread and number of electrons will go down two orders of magnitude or so. That means the detection rate of around 9 Hz would be less than 30 Hz laser rate (0.3 Compton photons per shot), and we can use coincidence scheme to make clean measurements of electron energy distribution.

The Fermilab linac needs special low current injector producing monochromatic beam for such experiment. In the IOTA channel it is desirable to increase the dispersion as much as possible after the bend and reduce the betatron horizontal size. The counters for Gamma quants can be chosen different to see if the results of experiment depend on the boundary conditions for absorbed scattered photons.

Typical accuracies of the laser beam alignment have to be about 10^{-4}. The angular spread of the electron beam angles has to be about the same. All misalignments have to be less than acceptable angle of Compton quanta that is 0.3x10^{-3} for the typical beam parameters (see eq. [5]).

WAVE FUNCTION SIZE EXTRACTION

The expected result is that Compton energy spectrum for electrons doesn't change after the quantum measurement and we don't see any broadening of scattered electron distribution. The wave function localization is very weak then and can't be measured. If we see broadening of the left distribution in Figure 1, it will indicate that some localization took place.

Here we would like to speculate on how we calculate wave function size from a measured image on the screen (see Figure 1, left distribution). We assume that the dispersion function D can be made large enough so that the betatron size of the beam can be made much smaller than the energy spread-related size, that is $D\dfrac{\delta E}{E}$. In addition, we assume the electron spin doesn't influence its motion much, and ignore the rest mass of the electron. In this case its motion is similar to the light and the Fourier transform of the energy spectrum (taken as square root of the measured distribution) produces the wave function in time-space representation. There is always a question of wave function slow phase that can't be determined from the measurement of this type – we assume it is close to being a constant.

Simple arguments give us the following picture: if the wave function gets localized after the measurement to one photon wave length, the energy spread will be equal to the photon energy meaning the left image in Figure 1 will overlap the right one. If the localization is about 10 wave lengths, the energy spread is around 10% of the photon energy (the width of the right distribution is about 10% of the distance to the right one), etc.

The parameters, chosen in this paper, allow us to see the localization size if it is below 100 backscattered photon wave lengths. If the localization length is larger, meaning the increase of the energy spectrum width is not seen, one needs to decrease the electron beam and backscattered photons energy spread further.

SUMMARY

In this paper we have presented examples of possible experiments at SNS and Fermilab on electron wave function localization due to Compton quantum scattering and its measurement by a detector. It is shown that if the localization of the electron wave function is below 100 wave lengths of backscattered photons, it will be possible to measure it with moderate modifications of existing and future facilities at SNS and Fermilab.

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